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The gas-surface interaction of a human-occupied spacecraft with a near-Earth object

W.M. Farrell [a,*], D.M. Hurley [b], M.J. Poston [c], M.I. Zimmerman [b], T.M. Orlando [d], C.A. Hibbitts [b], R.M. Killen [a]

[a] NASA/Goddard Space Flight Center, Greenbelt, MD, United States
[b] Johns Hopkins University/Applied Physics Laboratory, Laurel, MD, United States
[c] California Institute of Technology, Pasadena, CA, United States
[d] Georgia Institute of Technology, Atlanta, GA, United States

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Abstract

NASA's asteroid redirect mission (ARM) will feature an encounter of the human-occupied Orion spacecraft with a portion of a near-Earth asteroid (NEA) previously placed in orbit about the Moon by a capture spacecraft. Applying a shuttle analog, we suggest that the Orion spacecraft should have a dominant local water exosphere, and that molecules from this exosphere can adsorb onto the NEA. The amount of adsorbed water is a function of the defect content of the NEA surface, with retention of shuttle-like water levels on the asteroid at 10^{15} H_2O's/m^2 for space weathered regolith at $T \sim 300$ K.

Keywords: Asteroid; Water; Orion

1. Introduction

In 2012, a Keck Institute for Space Studies panel presented a unique concept for a human visit to a near-Earth asteroid (NEA), where the asteroid (or part of an asteroid) is captured, returned, and safely placed into lunar orbit. The object would then be visited multiple times by humans onboard the Orion multi-purpose crewed vehicle or MPCV (Asteroid Retrieval Feasibility Study, http://www.kiss.caltech.edu/study/asteroid/asteroid_final_report.pdf). This Asteroid Retrieval Mission (now called Asteroid Redirect Mission) is a primary Human Exploration initiative with the launch of a capture spacecraft scheduled for as soon as 2020.

The current mission design has a capture spacecraft powered by solar electric propulsion obtaining a ~4-m diameter boulder of a larger asteroid. This boulder will then be returned to cis-lunar space in the mid 2020s. Fig. 1 illustrates the human-occupied Orion spacecraft and ESA Service Module (ESM) in proximity with the captured airless body. The ARM Formulation Assessment and Support Team released their draft report identifying NEA 2008 EV_5 as a possible target (see http://www.nasa.gov/feature/arm-fast for more details).

Much like the Moon itself, after many years of exposure to the space environment (impact gardening, plasma sputtering), the weathered surface of the asteroid should have increased gas sorbency. A human system in proximity to the asteroid can thus alter the natural state of the interface at the atomic level by forward adsorption of spacecraft-originating outgassing molecules. In this work, we will examine the interaction of an outgassing Orion spacecraft

* Corresponding author. Fax: +1 301 286 3346.
E-mail address: william.m.farrell@nasa.gov (W.M. Farrell).

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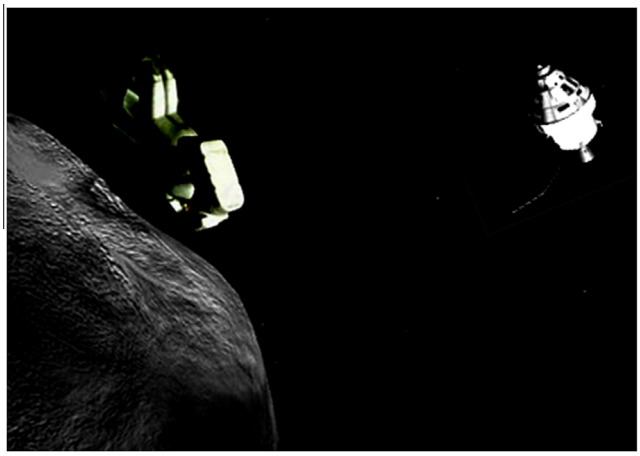

Fig. 1. An illustration of the Orion spacecraft (upper right) in the near-vicinity of the captured asteroid block (lower left). The asteroid block is ~5 m in size and the Orion spacecraft is ~200 m in distance away from the astronaut/asteroid.

with the asteroid. We will estimate the level of water anticipated that can be adsorbed onto the NEA surface – using the space shuttle outgassing as an analog. We demonstrate that the amount of molecular material that is adsorbed is a function of both NEA surface temperature and surface defect content; the latter being a function of the amount of previous space weathering the object has undergone. As recently described, (Dyar et al., 2010; Hibbitts et al., 2011; Poston et al., 2013, 2015), vacancy defect sites increase adsorption potentials and thus can trap water molecules for anomalously long times (Müller et al., 1996).

2. The water source: the space shuttle as an analog for Orion

The outgassing of a human occupied spacecraft was monitored and quantified during the Space Shuttle's SpaceLab-2 mission. Paterson and Frank (1989) examined the water ion cloud that forms about the shuttle from charge exchange processes with ionosphere gases using a plasma electrostatic analyzer on the Plasma Diagnostics Package sub-satellite in orbit about the shuttle. The water ion levels were found to be in excess of $10^4/cm^3$ in the anti-ram (tail) direction of the shuttle, and are consistent with the presence of a water neutral cloud in the near-shuttle vicinity with a concentration of $n_w > 10^9/cm^3$. Their modeling of the cloud indicates that the water neutral density is reduced to $n_w \sim 10^6/cm^3$ at a distance of 1 km from the shuttle, $n_w \sim 10^4/cm^3$ at 2 km from the shuttle and $n_w \sim 1/cm^3$ at 8 km from the shuttle (Paterson and Frank, 1989; Fig. 5).

While we do not know a priori the Orion water emission levels, we should assume that any spacecraft carrying humans will likely be providing a water atmosphere far greater in content than any atmosphere/exosphere provided by the NEA. For example, the lunar surface has an exospheric density of $n_{Moon} \sim 10^5/cm^3$ (see Stern (1999) and references therein). Much of this lunar atmosphere consists of gravitationally bound Argon-40. In the low g environment of a ~4-m asteroid, such heavy species would no longer be bound, and thus the asteroid escaping exosphere (called a corona (Morgan and Killen, 1998)) would be of even lower concentrations. As an example, for a dormant NEA, impact vaporization is expected to release neutral atoms at 10^{-15} kg/m^2 s or $\sim 10^{10}$ molecules/m^2 s (Cintala, 1992). Solar wind plasma sputtering would also occur at the surface at a rate of $R = FY$, with F being the solar wind flux at $5 \times 10^{12}/m^2$ s and Y the sputtering yield for silica at 0.03 (Johnson, 1990). This second process releases 10^{10-11} molecules/m^2 s. Since these molecules escape the small body at their ejection velocity (nominally, $<v> \sim 2$ km/s for $T = 4000$ K impact vaporization and $<v> \sim 3$ km/s for $T \sim 10{,}000$ K sputtering), the time-stationary density of the surface-released atoms is very low: $n_{nea} = F/<v> \sim 10–100/cm^3$. We thus conclude that the atmosphere of the human-occupied spacecraft ($n_w \sim 10^9/cm^3$) far exceeds by many orders of magnitude that liberated naturally from the small body ($n_{nea} \sim 10^2/cm^3$).

3. Water sticking to the asteroid surface

Recent temperature-programmed desorption (TPD) results (Poston et al., 2013, 2015) of water release from simulant and lunar samples are found to be describable by the first-order ($n = 1$) Polanyi-Wigner adsorption equation. The derived residency time of water molecules on a surface is:

$$\tau = \tau_o \exp(U/T) \quad (1)$$

where $\tau_o \sim 10^{-13}$ s is the inverse of the quantum frequency for the trapped energy state of the molecule in the interatomic potential (see Hunten et al., 1989; Fig. 13), U is the adsorption activation energy in eV, and T is the surface temperature in eV. The value of U ranges from low values <0.3 eV for uncomplicated surface crystals to >1 eV for surface with vacancy-type defect sites (i.e., possessing relatively deeper adsorption trapping well). The TPD lab work of Poston et al. (2013) quantified a population of high U value adsorption sites ($U \sim 0.6–1.2$ eV) on lunar simulant and albite.

Fig. 2 shows a water molecule residency time as a function of temperature and activation energy value. For unweathered or mildly weathered surfaces ($U < 0.3$ eV), the water residency time is small: less that a second. However, for surfaces with a large population of large-U valued adsorption sites ($U > 0.65$ eV), the water residency time or 'sticking time' can exceed 10^5 s for $T < 200$ K. For residency times longer than about 10^5 s, photo-dissociation of water molecules (Crider and Vondrak, 2000; DeSimone and Orlando, 2015) will become the dominant water loss process limiting surface residency times.

Fig. 3 shows the surface water molecules retained as a function of temperature and activation energy value. We assume a spacecraft-originating water flux of

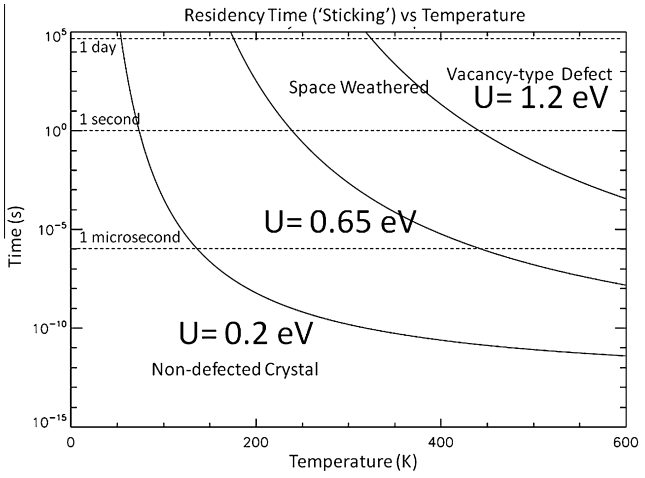

Fig. 2. Residency time for a water molecule at the body, for varying temperatures and activation energies (U).

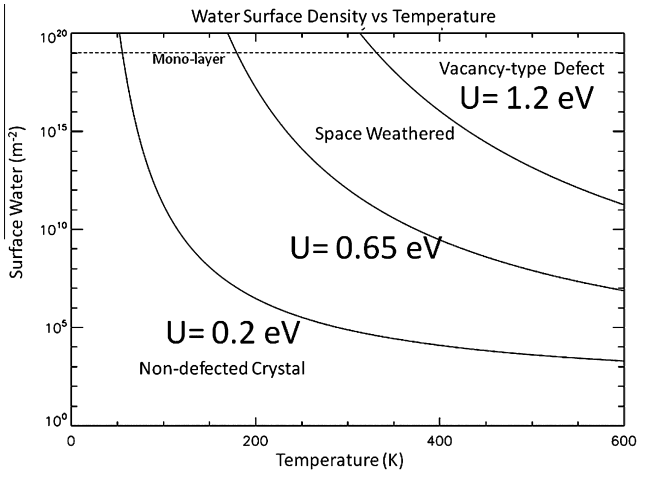

Fig. 3. The expected water surface density for a spacecraft source of $5 \times 10^{14}/m^2$ s.

$F = 5 \times 10^{14}/m^2$ s is incident on the surface, consistent with a nominal Space Shuttle water flux at a distance of 1 km from the orbiter (Paterson and Frank, 1989). In order to arrive at this equilibrium surface water concentration, we balance the spacecraft water influx against desorption losses, $\sigma = \Phi\tau$, where σ is the surface water concentration and τ is the residency time from Fig. 2. We also assume the water molecules are independent of each other, forming water-surface atom interactions as opposed to water-water surface interactions (true for low surficial coverage). For $\sigma > 10^{19}/m^2$, the water molecule surface density exceeds a monolayer and water surface sticking is via water-water interactions (Müller et al., 1996) which are not properly modeled herein. Thus, Fig. 2 applies best to partial water molecular surface coverage.

The results indicate that some forward contamination from Orion should be expected, but the amount of water that 'sticks' is a function of asteroid body temperature and maturity (defect density) of the asteroid surface. If we assume a lunar-like range in body temperatures (100–400 K) and adsorption activation energy values like those detected during TPD studies (Poston et al., 2013, 2015), then we might expect surface water concentrations above $10^{15}/m^2$ at cooler locations of the body.

4. Detailed modeling of water adsorption

Consider the water residency for a small rotating body and consider that the distribution of activation energy at the numerous adsorption sites are likely in a Gaussian-like continuum in values ranging from many low U valued sites to few high U-values sites. Assuming that the surface water coverage is initially sparse with only water-regolith atom interactions, we find that there are three general classes of interactions:

Low U values ($U < 0.3$ eV). As indicated in Fig. 2, even for low surface temperatures near $T = 100$ K, the residency time for low U valued adsorption of water is less than 10 μs. As such, these molecules are expected to be immediately lost in the low-g space environment, forming a low energy exosphere about the body. Eventual loss of the exospheric water will be via photo-dissociation (1.2 day lifetime) or photo-ionization (30 day lifetime) (Stern, 1999; Table 2). We note that U values this low are difficult to observe in the laboratory because they are below the energy of water-water surface interactions (~0.5 eV).

Intermediate U values ($0.3 \text{ eV} > U > 0.8$ eV). As shown in Fig. 2, for intermediate U values (~0.65 eV), we find water residency times or sticking times at a warm sub-solar point (>300 K) are less than a millisecond. Thus, any water molecules incident in such warm locations will be desorbed quickly, released from the surface back into the low-g space environment. However, these same adsorption sites at cooler regions below 200 K will trap the water molecule for over 10^5 s, possibly leading to a build-up of water along the terminator regions for a very slow rotating object. We thus develop a picture where water would be expected to collect at large solar zenith angles on the body, with increased surface concentrations towards the limb/terminator.

Large U values ($U > 0.8$ eV). Water molecules at these sites will experience greater trapping/sticking even at relatively warm temperatures. Given a Gaussian distribution of activation energies, we expect fewer adsorption sites above 1.0 eV, but for those few, they will trap and maintain water molecules at the surface for a large range in temperatures. We may expect some loss above 400 K (see Fig. 2, $U = 1.2$ eV with decreasing residency time near 400 K), but at 300 K these same adsorption sites can trap water molecules for $>10^5$ s.

As such, the spatial distribution of surface-bound water is expected to have contributions from the class of adsorptions having intermediate and large U values. Those waters of lower U value will be only briefly accommodated onto the surface. In order to model the effect of these contributions, we considered a distribution of activation energy for

240,000 water adsorptions sites, $f(U)$, defined by a Gaussian distribution with an adjustable central peak value, U_c, and an adjustable width, U_w. The Gaussian has the form: $f(U) \sim |\exp(-(U - U_c)^2/U_w^2)|$.

We consider the residency time (sticking time) at these sites under two different temperature profiles: (1) a lunar-like profile with $T \sim 300\ \mathrm{K}\ \mathrm{Cos}^{0.25}(\chi) + 100\ \mathrm{K}$ where χ is the solar zenith angle (e.g., similar to Eq. (9) of Crider and Vondrak, 2000) and (2) a constant 300 K temperature over all the surface. Since we do not know the rotation rate of the small object placed in orbit about the Moon, we consider (1) to be consistent with a slow rotator of a low thermally conductive object and (2) to be a fast rotator with the surface never quite experiencing long durations of hot or cold. Obviously, the model is sufficiently flexible to consider any temperature profile, but we consider these extremes to gain insight and derive general trends.

Fig. 4 shows fractional water content retained for the slow-rotator case given an $f(U)$ with $U_c = 0.0$ eV and $U_w = 0.4$ eV. The retained fractional content is defined as number of molecules that stick (with dwell times over 1 s) divided by the total number of water molecules incident on that portion of the surface. We chose $t > 1$ s to define a 'long' dwell time based on the time scale in Fig. 2, which ranges from $<10^{-10}$ s for warm, low U surfaces to 10^5 s which limits water dwell times via photo-dissociation. This fractional content then provides a probability of sticking given the applied distribution of activation energy states. Most of the adsorption sites have low U values, and thus at low χ (warm regolith) have a water residency time much less than 1 s. As shown in Fig. 4, the fractional content of sticking water molecules sharply increases with increasing χ (near the cooler limbs). As χ approaches 90°, the probability of an incident water molecule sticking to the surface for over 1 s approaches 10% for this specific distribution.

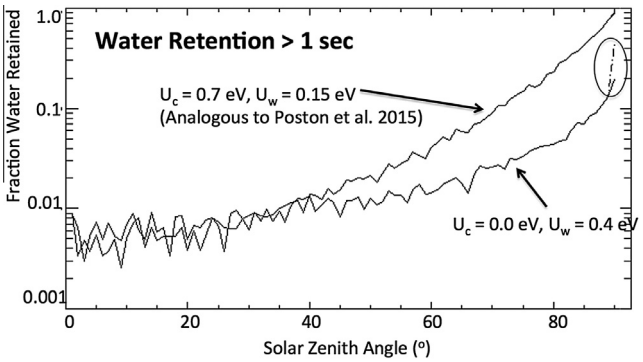

Fig. 4. The fraction of water sticking for >1 s as a function of SZA. Results are from two different Gaussian distributions of activation energy: One curve derived from a distribution with a peak in the density of energy states at 0 eV but with a 0.4 eV width, and the other curve from a distribution with a peak in the states at 0.7 eV and a 0.15 eV width (representative of the Poston et al. (2015) distribution of chemisorbed activation energy). The circle shows a dashed curve representative of the change in fraction when water-water interactions are considered (see text for details).

Since we do not know a priori the distribution of activation energy of the adsorption sites or temperature profile for the body placed in orbit about the Moon, we reran the model considering a number of $f(U)$ profiles under the slow (lunar-like T profile) and fast (uniform 300 K) rotation assumptions. We set $U_c = 0.0$ eV but vary the width of the distribution, U_w, from 0.1 to 0.6 eV, deriving water sticking for wider-width Gaussian distributions having progressively large number of adsorption sites with higher U values.

Table 1 shows the percentage of retained water molecules, stuck to the surface for greater than 1 s, under varying distribution widths, U_w. When the distribution width is $U_w = 0.1$ eV, there are no U values above 0.3 eV, and thus no molecules dwell greater than 1 s – they all leave the surface very fast. However, as U_w is increased, there is a larger fraction of adsorption sites with dwell times exceeding 1 s. For a broad distribution in activation energy ($U_w = 0.6$ eV) the number of sites with dwell times exceeding 1 s is over 10% for both the slow and fast rotation cases. The primary difference in these slow and fast rotation cases is that in the former, the long dwell times are found at large χ (at the limb) while for the fast rotator, locations of long dwell times are effectively uniformly distributed over all χ.

Poston et al. (2015) measured the distribution of activation energy for two Apollo lunar samples, and the two samples widely varied in their distribution of states. One had a $f(U)$ distribution with the majority of states below 0.6 eV. However, the second sample had a large set of sites with high U values which were considered chemisorbed sites where the water-surface bonding is chemically-strong. As shown in their Fig. 6a, this distribution peaked near 0.7 eV and had a half-width of about 0.3 eV.

We modeled this chemisorbed distribution as a centered-offset Gaussian with $U_c = 0.7$ eV and $U_w = 0.15$ eV and again considered the dwell-time for 240,000 water adsorption sites randomly placed over a slow-rotating small body surface. The fractional amount of water retained for >1 s is shown in Fig. 4. Due to the warm surface near the sub-solar point, there is ~0.5% retention of water. However, at large χ, the probability of sticking (for at least 1 s) increases, and exceeds 50% for χ over 85°. It is likely that the surface has a mix of weak physisorbed and stronger chemisorbed sites (Poston et al., 2015), and the fractional water retained lies between the curves shown.

4.1. Water-water interactions

An assumption made in these Monte-Carlo simulation runs is that each water-surface adsorption interaction is independent, and water molecules do not interact. This assumption holds best for sparse coverage. As such, a broad range of surface activation energy values are modeled, representative of defects, micro-roughness, and oxidation states/chemical traps at the surface.

However, if substantial water coverage develops, the sites at low and intermediate activation energy values

Table 1
Percent of water 'sticking' onto the surface of the small body (dwelling on surface for greater than 1 s), for a slow and fast rotation scenario. The width of the distribution of activation energy at the adsorption sites is increased from 0.1 to 0.6 eV, and shows an increased number of retained water molecules with increasing width in the distribution of U.

U_w ($U_c = 0.0$ eV)	% Water retained: slow rotator	% Water retained: fast rotator
0.1	0.0	0.0
0.2	0.02	0.003
0.3	0.4	0.7
0.4	2.2	4
0.5	6	10
0.6	11	17

may now be occupied by water. Due to its molecular polarity, the water-occupied low and intermediate energy sites now have their own trapping potential, with an activation energy near 0.5 eV to trap another water and initiate the formation of water clusters (Müller et al., 1996). Hence, when coverage becomes substantial, water-water interactions compete with water-regolith atom interactions.

This water-water effect can be examined by taking the distributions used in Fig. 4 (those assuming water-regolith atom interactions only) and now setting all adsorption site values with $U < 0.5$ eV to a new fixed value of $U = 0.5$ eV, where 0.5 eV is representative of the water-water activation energy. In essence, we purposely replace these sites with a population consistent with water-occupied states that would be involved in water-water interactions. This approach is likely an extreme since there still should be a population of water-unoccupied low energy surface sites in any real material.

We re-ran the simulation runs with the low energy limit of the applied $f(U)$ set at 0.5 eV, and find the fraction of water molecules retained for $t > 1$ s does not change substantially. The circle in Fig. 4 shows a dashed line of the mild increase in trapping via water-water interactions at the terminator in the $U_c = 0.0$ eV, $U_w = 0.4$ eV profile.

We conclude that adsorption sites with U values above 0.5 eV are involved in retaining water molecules for greater than 1 s, and water-occupied sites are not involved in retaining water for greater than 1 s (except at the coldest regions at the largest solar zenith angles). However, in these coldest regions (the circled, dashed line in Fig. 4), we may expect the development of surface water clusters (and with greater coverage, eventual icing). While we have discussed this cutoff of U values at 0.5 eV as water-water interactions, they may also be taken to represent physisorption.

5. Conclusions

We find that a human occupied spacecraft has the ability to outgas and forward-contaminate asteroidal objects nearby. In the case of a captured exposed boulder of an asteroid in the ARM mission, water originating from the Orion spacecraft body will likely adsorb to the weathered asteroid surfaces. The amount of adsorbed water on the surface of the asteroid is a strong function of body maturity and temperature. The former controls the number and nature of defects (i.e., the distribution of activation energy, $f(U)$) and the latter defines the surface energy that stimulates molecule escape. As indicated in Figs. 2 and 3, both variables play a significant role in trapping water to the surface. While much of this water will be transient, it is expected that the space weathered surfaces of the asteroid will have a population of adsorption sites that can trap water molecule for long times via relatively deep inter-atomic potentials.

We note that the ARM mission is not the first time one had to consider the effects of human forward contamination and outgassing on a sensitive near-by system: During the Apollo 17 mission, the Lunar Atmosphere Composition Experiment (LACE) was affected by the Lunar Module daytime out-gassing, creating ambiguities in interpretation (intrinsic atmospheric vs human exogenic sources) of detection of molecular species (see Stern, 1999, and discussion therein). Untangling these ambiguities was a motivating factor for developing the LADEE mission; this to obtain the exospheric composition of the fragile lunar near-surface environment prior to alteration by human explorers (LADEE Science Definition Team report, http://lunarscience.arc.nasa.gov/files/LADEE_SDT_Report.pdf, 2008). LACE observations provide some level of validation to the conclusions herein that human system out-gassing creates a local atmosphere far in excess of that intrinsic to the fragile small body.

We provide a set of recommendations that compliment and enhance those in the ARM-FAST report:

(1) The MPCV should include an IR system to sense the 3 μm reflection features from the asteroid to derive the amount of water being adsorbed on the body as the spacecraft approaches.
(2) It might also be of value to examine the Orion system from an IR instrument placed on the body, to determine the amount of adsorbed water on the MPCV, and how it might vary in time (local sunlight temperature of the spacecraft, etc.). In essence, as we examine the water interaction with the small body, we also want to look back at the spacecraft to derive the water content at its source.
(3) Analogous to the shuttle's SpaceLab-2 mission, one could even envision the release a free-flying cubesat to understand the ongoing gas exchange as the Orion system approaches the fragile body (admittedly, releasing cubesat systems in near-vicinity to the human spacecraft that is also in a rendezvous with the asteroid would be operationally challenging).
(4) One other possible activity is to build a 'defect garden' on the asteroid to examine the external water interaction with regolith that has been exposed, recently upturned by astronauts, and fractured via a

hammer by astronauts. One could even imagine also overlying a 'patch plate' of various material for comparison in the defect study. An IR system could then determine the amount of water retained by each element of the regolith and patch.

(5) We recommend placing a cover over the asteroid at the time of capture, which will likely reduce the forward contamination from the Orion environment. Activity associated with the proposed defect garden could then be performed using the uncovered, expose surface of the asteroid.

The build of a defect garden would be analogous to performing laboratory adsorption/desorption studies (Hibbitts et al., 2011; Poston et al., 2013, 2015), but now in a real space environment where there are numerous exospheric species all competing for the high U 'sticking' sites.

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